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Published in:
Journal of Environmental Management

DOI:
10.1016/j.jenvman.2022.115373

Publication date:
2022

Document version
Publisher's PDF, also known as Version of record

Document license:
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Citation for published version (APA):
Impacts of empty fruit bunch applications on soil organic carbon in an industrial oil palm plantation

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ARTICLE INFO

Keywords:
Empty fruit bunch
Permanganate oxidisable carbon
Oil palm
Sumatra

ABSTRACT

Extensive oil palm plantations have often resulted in the decrease of soil organic carbon (SOC). Several options exist to counter this, such as recycling empty fruit bunches (EFB) as a soil amendment. However, the extent to which EFB increase SOC has been disputed. Since EFB could also be used as a climate change mitigation tool, it is necessary to truly understand their impact on SOC. The investigation of the impact of nine EFB treatments (differing in frequency and application rates) on a 27-year-old large-scale experiment (Lampung, Sumatra, Indonesia) revealed that, while EFB impacts are heterogeneous throughout the plantation, they can positively affect total SOC and permanganate oxidisable carbon (POX-C) both at shallow and deep depths (measured up to 100 cm). POX-C was closely correlated to SOC, but showed significant increases compared to the untreated control in all treatments, while total SOC was only increased in a few treatments with small and frequent rates of EFB application. Overall, between 12 (±16) and 56 (±12) t ha⁻¹ of carbon were sequestered under the harvesting path after 21 years. Focussing on the mineral nutrition value of the EFB, oil palm companies apply a rate of 60 t of EFB every second year for their commercial production, and the analysis of three commercial plots showed that the commercial rate only increased POX-C while it had no effect on the total SOC and SOC stocks. It seems obvious that a change of paradigm is necessary to consider EFB recycling as a new management perspective, where the potential for carbon sequestration becomes an important variable for climate change mitigation besides the initial objective of integrating EFB application into the fertiliser management plan of a plantation.

1. Introduction

Palm oil is extracted from the fruit of oil palms (*Elaeis guineensis* Jacq.) and is a worldwide economically important commodity (Tao et al., 2017). Together, Malaysia and Indonesia provide 86.5% of the 57 million t global palm oil production (FAO, 2019). In the course of a decade (2003–2014), Indonesia doubled its area dedicated to oil palms on the islands of Sumatra and Kalimantan (FAO, 2019; Khatiwada et al., 2018; Petrenko et al., 2016). The International Union for Conservation of Nature (IUCN) estimated that approximately 50% of the area planted with oil palm between 1972 and 2015 expanded into forested lands (Meijaard et al., 2018), inducing large environmental impacts, such as greenhouse gas emissions, loss of biodiversity and decreasing soil carbon stocks with negative impacts on soil quality (Campbell and Doswald, 2009; Obidzinski et al., 2012; Petrenko et al., 2016). The latter may be a consequence of decreased inputs and/or increased soil organic matter (SOM) decomposition due to soil disturbance (Guillaumet al., 2015).

In order to restore and maintain soil health, including the restoration of the soil carbon pool, and to improve oil palm nutrition, several options are already known and often implemented. These include the growing of leguminous green manure at the beginning of the growth cycle of the palm, reducing and selecting chemical herbicide applications to maintain an understory between the palms as well as recycling organic residues, such as empty fruit bunches (EFB) or palm oil mill

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https://doi.org/10.1016/j.jenvman.2022.115373
Received 20 October 2021; Received in revised form 27 April 2022; Accepted 19 May 2022
Available online 29 May 2022

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Efluent (Carron et al., 2016). EFB are usually applied in oil palm plantations as a substitute for inorganic fertilisers or as an organic soil amendment. They are the structural part of the fruit bunches, which have been emptied of the fruits that are used for oil extraction (Tao et al., 2017). A few decades ago, they were traditionally incinerated, but, because of the associated air pollution and greenhouse gas emissions, they are nowadays recycled and directly applied on the plantation as a mulch substrate in order to valorise their nutrient content (Rosenani et al., 2011, 2016; Tao et al., 2017).

Mulching with EFB is known to improve the physical and chemical properties of the soil, to provide plant nutrients and to enhance the yield of the palms (Carron et al., 2015; Comte et al., 2013; Rosenani et al., 2011, 2016; Tao et al., 2017). However, since oil palm plantations are often divided into different management zones, there is a large spatial variation in organic matter input (Rahman et al., 2018). In addition, the effects of EFB application are reported to vary with application rates and duration (Carron et al., 2016; Comte et al., 2013; Rosenani et al., 2011). Furthermore, reports on the potential of EFB to sequester soil carbon are inconsistent. Some studies report an increase in SOC after EFB application to soil, either localised (Carron et al., 2015) or on a plantation scale (Comte et al., 2013). When different soil depths were sampled, the increase was either reported to be restricted to the top soil layer (Rosenani et al., 2016) or was also found in deeper layers (Rosenani et al., 2011; Tao et al., 2017). In other studies, no increase in soil carbon was observed after EFB application (Carron et al., 2016). Tao et al. (2018) even demonstrated that SOC decreased when high rates of EFB (90 t ha$^{-1}$) were applied.

The objectives of this study were therefore to investigate the spatial heterogeneity of the long-term impact of EFB on soil carbon content by investigating both the total SOC pool and the more labile permanganate oxidisable carbon (POX-C). The latter allows to quickly assess a labile carbon pool, and has been claimed to be a sensitive indicator of the impact of different management techniques on soil carbon (Bruun et al., 2013; Culman et al., 2012; Hurisso et al., 2016; Well et al., 2003). Soil was sampled in a long-term experiment in an industrial oil palm plantation in Lampung, Sumatra. The trial was originally designed in the late nineties to determine the most appropriate EFB application conditions, in terms of rate and frequency of application, for a complete integration of EFB recycling into the fertiliser plan of the plantation. While the agronomic aspect of the waste recycling was the main objective at that time, the long-term treatments now provided a unique opportunity for a first evaluation of the capacity of carbon storage in the soil of South Sumatra. The study was then also extended to a commercial area with and without EFB application.

2. Material and methods

2.1. Site description

The estate of Sungai Buaya (SBYE) is located in the province of Lampung on the island of Sumatra, Indonesia. The climate is classified as a tropical humid climate (Tao et al., 2017). The dry season usually extends from July to September (exceptionally from June to November under severe El Niño conditions), while the rainy season usually lasts from November to May.

2.2. Long-term experiment

Before the area was developed into an oil palm plantation, it was covered by a secondary tropical forest. The palms (of Marihat genetic origin) were planted in 1992 with a density of 143 palms per hectare. Until the start of EFB application in January 1999, inorganic fertiliser (NPK) was applied both during the immature (≤4 years old) and mature (>4 years old) stage of the palms. Oil palms are grown until they reach the age of approximately 25 years. The trial comprised 12 treatments, i.e. 9 EFB treatment plots and 3 control plots (100% inorganic fertiliser) with five replicates per treatment, adding up to 60 plots with 30 palms each. Each replicate was surrounded by an isolating trench to reduce the poaching effect between plots, which initially measured 1.5 m in depth when the trial was set up in 1999. EFB treatments consisted of three application rates (fresh weight): 30 t ha$^{-1}$ (210 kg/palm) (low rate), 60 t ha$^{-1}$ (420kg/palm) (normal rate) and 90 t ha$^{-1}$ (630kg/palm) (high rate). These were combined with three application frequencies: once per year (last applied in 2019), once every second year (last applied in 2019) and once every third year (last applied in 2017). Each application was performed in the same season between May and June.

Thus, throughout the trial, between the first application in 1999 and the last one in 2019, there had been 21, 11 and 7 applications of EFB with a frequency of application of every year, every second year and every third year respectively. In the following, treatments will be abbreviated as e.g. “30t/2 years” for an application of 30t EFB ha$^{-1}$ every second year. In the years between EFB applications, urea was applied with a quantity increasing with the EFB application rate in order to obtain a comparable nitrogen input every year for each application rate (Table 1). When EFB were applied, triple superphosphate or rock phosphate was spread on top of it to balance the nutrient availability in line with the requirement of the palms. The three control plots per replica received inorganic fertiliser instead of EFB, applied twice a year. The nutrient additions with the different treatments can be seen in Table 1.

The EFB were applied on each side of the harvesting paths, which are located on every second row of the plantation (Fig. 1). Fronds were cut down every week during harvesting time and one half was left on the other rows (wind-rows) of the plantation while the other half was piled between every two palms. At the foot of the palm, a weeded bare ground circle (WC) (with a radius of approximately 1.5 m) was left free to ease the collection of the fruits. The herbicides applied within the circle and on the harvesting paths were Roundup (glyphosate) and Ekafulon (Metsulfuron-methyl). They were applied four times a year.

2.3. Commercial area

Under commercial conditions, four blocks (including one control block) south of the trial area were sampled. The area had been covered by a secondary tropical forest until it was transformed into a palm oil plantation in the early 1990’s. EFB applications at a rate of 60t/2 years started on these blocks more than 20 years ago. The application consistently alternated between the left and right side of the harvesting path. The last EFB application before sampling was in May–June 2019 and the sampling of commercial plots was performed in February–April 2020. The application of mineral fertilisers was adapted according to yearly foliar analyses.

2.4. Soil sampling

Three replicates (replicates I, III and V) were sampled to cover the soil heterogeneity of the long-term experiment. The soil in the plantation is classified as Ultisol (Typic Kandiudults) with an average pH of 3.9 (measured in the untreated control plots at a depth of 0–25 cm using 1 M KCl and a 1:2.5 soil:solution ratio). Overall, replicate I had a more sandy clay texture (51% sand, 8% silt, 40% clay) while replicates III and V had a higher clay content (26% sand, 18% silt, 56% clay and 33% sand, 13% silt, 54% clay respectively). Per replicate, all treatment plots and one of the three control plots were sampled. On each trial plot, one palm was chosen in the second row and the second column in the north-western part of the plot. In the commercial plots, three blocks receiving EFB were chosen, i.e. 9 palms distributed among 5 rows were sampled. One control block (without EFB application) was chosen for the commercial samples and 5 palms were sampled among three rows.

Under both the trial and commercial conditions, the three sites for soil sampling were: under the EFB (centre of the application, hereafter referred to as the harvesting path), under the fronds (centre of the application) and within the WC (1 m away from the palm) (Fig. 1). It is
worth noting that, since EFB were applied on both sides of the harvesting path of the commercial blocks, both sides were sampled and analysed. Samples were taken at different depths based on observations made on a 1 m-depth soil profile established in SBYE under the EFB location close to a palm that received 60t/3 years (last application in May 2018). The soil samples included 2 layers with very clear visual colour difference, i.e.: 0–10 cm and 10–25 cm. Two additional layers (25–55 and 55–100 cm) were chosen in order to capture the potential variation within the 25–100 cm layer, which looked homogeneous. Volume-specific soil samples were taken for the bulk density (BD) determination. The additional samples were composite samples of 3 subsamples, which were taken from the centre of the soil layers.

2.5. Soil analysis

After sampling, the samples were air-dried for 3–5 days. Each soil sample was sieved to 0.5 mm. The total SOC was determined by the Walkley-Black method (Nelson and Sommers, 1982). The SOC stocks were calculated following the equivalent soil mass (ESM) method using the spreadsheet developed by Wendt (2012). Reference soil masses of 1200t, 3000t, 7000t, and 12000t ha⁻¹ were chosen, as they best represented the layers sampled (Wendt and Hauser, 2013). The calculations were based on the BD of the different soil layers as well as the SOC concentration measured using the Walkley-Black method.

The analysis of POX-C was performed based on the protocol of Weil et al. (2003) which was modified by Culman et al. (2012). Briefly, 2 mL of 0.02 M KMnO₄ and 18 mL of deionised water were added into 50 mL Erlenmeyer flasks containing 2.5 g of air-dried soil. The tubes were shaken for 2 min precisely at 120 rpm on an oscillating shaker. The soil was left to settle for 10 min and 0.5 mL of the supernatant were transferred into another 50 mL tube and mixed with 49.5 mL of deionised water. The sample absorbance was read using a Cary 50 (Agilent) and software version 3.00 (182).

2.6. Statistical analysis

Statistical analyses were conducted using R 4.0.5. The impacts of EFB application were assessed using a linear mixed model (LMM) with fixed effects of Treatment, Depth, Location and all their interactions as well as the factor Block in interaction with Depth and Location (two-factor interactions) and random effects of the variables Plant (combination of Treatment and Block) and Sample (combination of Treatment, Location and Block). For the commercial plots, both the POX-C and total SOC content of the two application sites on each side of the harvesting path were averaged and averages were analysed using LMMs with fixed effects of Block, Depth and Location and their interactions, as well as random effects of Plant and Sample. For the subsample from the harvesting path in the long-term experiment, LMMs with fixed effect of

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Nutrient addition to the different treatments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>EFB applied per palm</td>
</tr>
<tr>
<td>t FW/ha</td>
<td>Kg DW palm⁻¹</td>
</tr>
<tr>
<td>30/year</td>
<td>73.5</td>
</tr>
<tr>
<td>30/2 years</td>
<td>73.5</td>
</tr>
<tr>
<td>30/3 years</td>
<td>73.5</td>
</tr>
<tr>
<td>60/year</td>
<td>147</td>
</tr>
<tr>
<td>60/2 years</td>
<td>147</td>
</tr>
<tr>
<td>60/3 years</td>
<td>147</td>
</tr>
<tr>
<td>90/year</td>
<td>220.5</td>
</tr>
<tr>
<td>90/2 years</td>
<td>220.5</td>
</tr>
<tr>
<td>90/3 years</td>
<td>220.5</td>
</tr>
<tr>
<td>Control</td>
<td>n/a</td>
</tr>
</tbody>
</table>

a Calculations were based on an average content of N: 0.8%, P: 0.098%, K: 2.06% DW EFB (Sinarmas, unpublished data).

b In the EFB treatments, K addition was exclusively from EFB, while in the control treatment, only mineral K was added.

Fig. 1. Sampling locations.
Treatment, Depth and Block as well as Treatment\textsuperscript{+}Depth and Block\textsuperscript{-}\textsuperscript{+}Depth interactions and random effect of Sample were furthermore realised for total SOC and POX-C. The SOC stocks were analysed using a Two-Way ANOVA with effect of Treatment and Block under trial conditions and by a One-Way ANOVA with effect of Block under commercial conditions. Effects were assessed using marginal means (emmeans) and all treatments were compared to the control using Dunnnett’s adjustment of p-values. The level of significance was set at 0.05. All data were checked for normality and homogeneity of variance and, if needed, log transformed. In order to distinguish between the trial and commercial data, they are hereafter referred to as “TR” and “COM” respectively.

3. Results

3.1. Effects of EFB applications on the different carbon pools under trial conditions

Both total SOC\textsubscript{TR} and POX-C\textsubscript{TR} and total SOC\textsubscript{COM} and POX-C\textsubscript{COM} were significantly linearly correlated ($R^2 = 0.80$ and $R^2 = 0.93$ respectively, Fig. 2). On average, the POX-C\textsubscript{TR} values represented 3.5% of the total SOC\textsubscript{TR} and POX-C\textsubscript{COM} represented 2.9% of the total SOC\textsubscript{COM}.

Total SOC\textsubscript{TR} and POX-C\textsubscript{TR} were significantly affected by depth, location and treatment, but there were no significant interactions between the factors. Under the trial conditions, both the total SOC\textsubscript{TR} and POX-C\textsubscript{TR} values significantly decreased with depth and so did the difference between the layers (Figs. 3 and 4). Total SOC\textsubscript{TR} across all treatments and depths was increased compared to the control in all treatments, but differences were only significant for treatments 30 t/ year, 30 t/3 years and 60 t/year. POX-C was significantly increased in all EFB treatments (Fig. 3, A + B). The total SOC\textsubscript{TR} and POX-C\textsubscript{TR} concentrations were significantly higher under the harvesting path than under the WC (22.0% and 23.3% respectively) and the fronds (18.8% and 17.2% respectively) (Fig. 4). Under the harvesting path, differences between total SOC\textsubscript{TR} concentrations were very similar to those over all locations and again only significantly increased for treatments 30 t/ year, 30 t/3 years and 60 t/year, probably because differences were most pronounced in the upper soil layer (Fig. 3 C). Generally, lower application rates seemed to increase total SOC\textsubscript{TR} to a larger extent than higher application rates, which sometimes led to SOC concentrations below that of the control, especially at lower depths. There was no overall significant treatment effect for POX-C\textsubscript{TR} under the harvesting path ($p = 0.06$). However, in contrast to total SOC\textsubscript{TR} and POX-C\textsubscript{TR} over all locations, differences were visible in the deeper soil layers under the harvesting path (Fig. 3 D). Especially in the soil top layer under the harvesting path, the ratio of POX-C\textsubscript{TR} to SOC\textsubscript{TR} was generally higher in the treatments receiving 90t EFB compared to the ones that received 60t or 30t. In the deeper soil layers, the treatments had relatively more POX-C when EFB had been added every year or every second year compared to an addition only every third year.

In line with the results of the SOC concentrations, the EFB treatments 30 t/ year, 30 t/3 years and 60 t/ year had SOC\textsubscript{TR} stocks that were significantly higher than the control (Table 2). The significance of the 30t/3 years’ treatment was probably due to the extraordinarily high total SOC\textsubscript{TR} content measured in the 0–10 cm layer in this treatment (Fig. 4). The two treatments 30 t/year and 60 t/year sequestered a significant amount of carbon under the harvesting path, i.e. more than 50 t ha$^{-1}$ corresponding to more than 2 t ha$^{-1}$ year$^{-1}$ (Table 3). Relatively, i.e. comparing the carbon stocks to 100 cm depth with the total input over the last 21 years, the highest sequestration rates were observed in all treatments applying 30t and in the treatment 60t/3 years. Sequestration rates ranged between 40% and 50% in those treatments, with the exception of 30t/3 years, where the SOC\textsubscript{TR} stocks present in 2019 were higher than the amount added throughout the trial. However, as already mentioned, the total SOC\textsubscript{TR} concentration measured in the topsoil layer was, especially in one of the replicates, exceptionally high in this treatment. The lowest absolute and relative sequestration rates were observed in the treatments applying 90t. The relative sequestration was highest after application every third year for the 90t treatments, which was a trend that was also observed for the 30t and 60t treatments.

3.2. Effects of EFB application on the different carbon pools under commercial conditions

Under commercial conditions, the location did not impact total SOC\textsubscript{COM} or POX-C\textsubscript{COM}. Therefore, Fig. 5 only represents the results under the harvesting path. Total SOC\textsubscript{COM} was only affected by the depths, i.e. total SOC\textsubscript{COM} decreased with increasing soil depth. POX-C\textsubscript{COM} was similarly affected by the depths, but also significantly (71%) higher under EFB application than in the control conditions (over all depths). No impacts were observed of EFB application on the SOC\textsubscript{COM} stocks under the harvesting path (Fig. 6).

4. Discussion

4.1. The spatial heterogeneity of the impact of EFB application

No interaction was found between the locations and treatments for POX-C\textsubscript{TR} and total SOC\textsubscript{TR}, showing that the treatments affected the carbon content in all locations in a similar way. However, under the trial conditions, the soil consistently had significantly higher total SOC\textsubscript{TR} and POX-C\textsubscript{TR} concentrations under the harvesting path than under the WC and under the fronds. The fact that under the commercial conditions no similar claim could be made may be due to the lower precision of EFB application under commercial settings. Under the trial conditions, the EFB are carefully weighed, while on commercial plots they are applied using an empty bunch spreader, which impedes a regular distribution on the ground due to the variability of the EFB size.

The impacts of EFB have been shown to differently impact different locations within plantations in various studies. Carron et al. (2016), who investigated the heterogeneity of the impacts of EFB application on soil quality, did not see an effect of EFB application. The fact that EFB did not increase soil carbon could be due to the duration of the application. Indeed, in their study, the EFB had been applied for only 11 years, which is half as long as the application time in this study. Tao et al. (2016) concluded that the regular addition of EFB to the harvesting path was taking the SOC concentration to a similar level as in the place where the fronds were piled (pruned fronds piled in that area represented a volume of 5 to 13t of dry biomass per year). This is not in accordance with the present study, which points towards a spatial heterogeneity – at least under trial conditions – of the total SOC\textsubscript{TR} and POX-C\textsubscript{TR} concentrations.
Fig. 3. Total SOC\textsubscript{TR} (A, C) and POX-C\textsubscript{TR} (B, D) over all locations (A, B) and under the harvesting path (C, D) for all treatments at the four sampled depths. Error bars represent standard errors.

Fig. 4. Comparison of SOC\textsubscript{TR} (A) and POX-C\textsubscript{TR} (B) under the sampling locations at different depths over all treatments. Error bars represent standard errors.
the harvesting path.

4.2. Effects of different EFB treatments on soil carbon

Table 3

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total C input (t ha$^{-1}$)</th>
<th>Carbon sequestered (t C ha$^{-1}$) $^a$</th>
<th>Annually sequestered amount (t C ha$^{-1}$ y$^{-1}$) $^c$</th>
<th>C sequestered of total C input (%) $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 t/year</td>
<td>108</td>
<td>51 ($\pm$14)</td>
<td>2.4 ($\pm$0.7)</td>
<td>41 ($\pm$16)</td>
</tr>
<tr>
<td>30t/2 years</td>
<td>57</td>
<td>23 ($\pm$9)</td>
<td>1.1 ($\pm$0.4)</td>
<td>41 ($\pm$16)</td>
</tr>
<tr>
<td>30t/3 years</td>
<td>36</td>
<td>53 ($\pm$11)</td>
<td>2.5 ($\pm$0.5)</td>
<td>41 ($\pm$16)</td>
</tr>
<tr>
<td>60 t/year</td>
<td>216</td>
<td>56 ($\pm$12)</td>
<td>2.7 ($\pm$0.6)</td>
<td>26 ($\pm$6)</td>
</tr>
<tr>
<td>60t/2 years</td>
<td>113</td>
<td>27 ($\pm$19)</td>
<td>1.3 ($\pm$0.9)</td>
<td>41 ($\pm$16)</td>
</tr>
<tr>
<td>60t/3 years</td>
<td>72</td>
<td>35 ($\pm$6)</td>
<td>1.7 ($\pm$0.3)</td>
<td>41 ($\pm$16)</td>
</tr>
<tr>
<td>90 t/year</td>
<td>324</td>
<td>14 ($\pm$1)</td>
<td>0.7 ($\pm$0.0)</td>
<td>4 ($\pm$0)</td>
</tr>
<tr>
<td>90t/2 years</td>
<td>170</td>
<td>12 ($\pm$16)</td>
<td>0.6 ($\pm$0.8)</td>
<td>7 ($\pm$10)</td>
</tr>
<tr>
<td>90t/3 years</td>
<td>108</td>
<td>23 ($\pm$10)</td>
<td>1.1 ($\pm$0.5)</td>
<td>21 ($\pm$9)</td>
</tr>
</tbody>
</table>

$^a$ The total amount of carbon added in the different EFB treatments throughout the trial period was calculated with a total carbon content of 49% (dry weight) (SMART RI, unpublished data).

$^b$ t C in EFB treatment – t C in control treatment. The carbon stocks were measured using the ESM method.

$^c$ The data presented are the extrapolation of the carbon stocks present under the harvesting path. Numbers in parentheses represent standard errors.

Several studies have investigated the long-term effect of different rates of EFB application on soil characteristics such as total SOC. The study by Tao et al. (2017) and Rosenani et al. (2011) reported an impact of EFB application on the total SOC both on the topsoil (0–20 cm) and on deeper layers (20–100 cm). After short-term application, several studies showed that the addition of EFB did not increase the total SOC (Carron et al., 2016). Carron et al. (2015) suggested that EFB will impact total SOC only after 18–24 months of application. This study’s results support the data from Tao et al. (2017), as we found only slightly higher SOC concentrations, which could probably be explained by the difference in length of EFB application. In this study, EFB had been applied for 6 additional years compared to the study by Tao et al. (2017). Thus, it is important to consider both the length of EFB application and the sampling depth when investigating and comparing studies that have looked at the impact of EFB application on soil carbon (Carron et al., 2015; Gross et al., 2018; Rahman et al., 2018; Wendt and Hauser, 2019).

POX-C has been found to represent a comparatively labile, but processed C pool in soil (Calman et al., 2012) available for soil microbial processes and an increased POX-C value has been associated with long-term carbon sequestration (Calman et al., 2012, 2013; Hurisso et al., 2016). Accordingly, POX-C$_{TR}$ and POX-C$_{COM}$ were increased in all treatments that had received EFB inputs in our study. POX-C has often been reported to be a sensitive indicator of organic matter input (Liang et al., 2012; Bongiorno et al., 2019) and a relative enrichment of POX-C in treatments receiving high rates or frequent/recent applications was also observed in our study. Tirol-Padre and Ladha (2004) investigated the reactivity of organic compounds with KMnO$_4$ and found it to be a good indicator of lignin content, which could also be the reason for the relatively higher POX-C contents in the treatments receiving high amounts of EFB.

While the analysis of POX-C$_{COM}$ shows that the EFB treatment of 60 t/2 years significantly increased this distinct soil carbon pool, no increase of total SOC$_{COM}$ was observed. Consequently, there was no significant impact of commercial EFB application on SOC$_{COM}$ stocks either. This result supports the analysis of the trial data, which also showed that a rate of 60 t/2 years did not significantly increase carbon stocks compared to the control. However, in the commercial plots the 60t were applied alternately on each side of the harvesting path, while under the trial conditions the EFB were evenly distributed. Generally, a more irregular EFB application is typical under commercial conditions, which reduces the measurable impact of EFB on soil carbon (Comte et al., 2013).

This has often been indicated by researchers as a characteristic of oil palm plantations (Carron et al., 2016; Frazao et al., 2013; Khasanah et al., 2015; Rahman et al., 2018). In addition, the trial area was originally rather heterogeneous, which may still affect the results of the present study.

4.2. Effects of different EFB treatments on soil carbon

Under experimental conditions 21 years after the first application, the total SOC$_{TR}$ concentrations were increased in all EFB treatments compared to the control, although this effect was only significant for the treatments 30t and 60 t/year and 30t/3 years. In contrast, all treatments receiving EFB inputs had a significantly increased POX-C$_{TR}$ concentration. The most efficient treatments (30t and 60 t/year) resulted in an increase of carbon stocks by 61% compared to the control. It is, though, important to keep in mind, that the carbon stocks are extrapolations from one location and that soil sampled under the harvesting path does not truly represent the quantity of carbon per hectare in the plantation.

While the analysis of POX-C$_{COM}$ shows that the EFB treatment of 60 t/2 years significantly increased this distinct soil carbon pool, no increase of total SOC$_{COM}$ was observed. Consequently, there was no significant impact of commercial EFB application on SOC$_{COM}$ stocks either. This result supports the analysis of the trial data, which also showed that a rate of 60t/2 years did not significantly increase carbon stocks compared to the controls. However, in the commercial plots the 60t were applied alternately on each side of the harvesting path, while under the trial conditions the EFB were evenly distributed. Generally, a more irregular EFB application is typical under commercial conditions, which reduces the measurable impact of EFB on soil carbon (Comte et al., 2013).
would be necessary to explain the observed effects seems rather unlikely. Another explanation could be a decreased carbon use efficiency at high application rates that was observed e.g. by Fang et al. (2018) after a high input of wheat residues and that could possibly be attributed to insufficient nutrient supply to the decomposer community.

The analysis of the trial conditions clearly shows that EFB application also impacts soil carbon at lower depths (at least up to 100 cm, the maximum depth sampled in our study), which has been shown by other studies (Rosenani et al., 2011). In accordance with Rosenani et al. (2011), this study shows that the increase of both total SOC_TR and POX-C_TR values decreases with depth. The decrease of the POX-C concentration is solely based on the decrease in the size of the carbon pool, as the sensitivity of the POX-C is not affected by depth, meaning that the indicator can also be useful at lower depths (Culman et al., 2012). However, the proportion of POX-C in total SOC increased with depth in some of the treatments, especially those with frequent application rates under the harvesting path. This is in contrast to other studies observing a decrease of the proportion of labile C pools with increasing depths (Yang et al., 2009). However, also Goodrick et al. (2015) observed a high incorporation of organic matter from pruned fronds to greater soil depths and attributed the observation to a high activity of soil fauna in oil palm plantations.

4.3. Management implications

The initial objective of the trial set up in 1999 was to contribute to the development of an operational policy for the integration of EFB recycling into the fertilisation plan of plantations i.e. EFB applications as a substitute for inorganic fertilisers. However, the results of our study indicate a considerable C sequestration potential, especially when smaller rates of 30t or 60t are applied frequently (Table 3). Each hectare of mature oil palm will produce around 5 to 8 t of EFB yearly, depending on rainfall variation (Sinarmas, unpublished data). Thus, a new application strategy could be defined in which maximising carbon sequestration is the primary objective, while integrating EFB recycling into the palm’s fertilisation management would be a secondary agronomical objective. This would also be in line with the potential role for agriculture to contribute to climate change mitigation. To confirm this approach, a new study should be initiated to determine the optimal rate of EFB to be applied (i.e. the level of carbon sequestration to be targeted), when also taking into account the amount of inorganic fertiliser required to supplement EFB to ensure optimum mineral nutrition of the palms to reach the targeted yield level. The costs and environmental impacts associated with the transport and application of EFB and inorganic fertilisers will certainly represent a key parameter in such an approach.

5. Conclusion

This study showed that the long-term application of EFB can sequestrate considerable amounts of C per hectare, depending on the frequency and rate of application. However, the effect was found to be spatially variable and highest under the harvesting path. While the larger portion of this carbon was stored in the upper soil layer, increased carbon stocks were also observed in lower soil depths. Larger EFB application rates (90t) were not efficient in terms of carbon sequestration, but small and frequent rates (e.g. 30t or 60 t/year) best utilised the soil carbon sequestration potential of EFB applications.

The results of this study highlight the necessity for a change of
paradigm in order to consider EFB recycling in new management perspectives, where the potential of carbon sequestration becomes an important variable for climate change mitigation. For that purpose, further dedicated experiments should be initiated to determine new models for the utilisation of EFB recycling in agronomic and environmental balance, also under future climate change scenarios and in other geographical regions.

Credit author statement

Lauriane Marie Noirot: Investigation, Writing – original draft, Methodology, Resources; Dorette Sophie Müller-Stöver: Supervision, Writing – Review & Editing, Visualization; Resti Wahyuninghis: Validation, Resources, Data curation; Helle Sørensen: Formal analysis;

Sudarno: Software, Methodology; Abedgeno Simamora: Resources, Methodology; Pujianto: Conceptualization, Methodology, Resources; Suhardi: Methodology, Supervision, Project administration; Jean-Pierre Caliman: Conceptualization, Supervision, Writing – Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

We warmly thank Novila and the entire SMART RI analytical laboratory team for their assistance with the soil analyses. We are extremely grateful for the help we received from the team working in Sungil Buaya, especially for their great help with the soil sampling. Finally, we would like to thank SMART RI for funding this research.

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